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Suitability Modeling of Lake Sturgeon Habitat in Five Northern Lake Michigan Tributaries: Implications for Population Rehabilitation

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Abstract

The availability of lotic spawning, staging, and nursery habitats is considered a major factor limiting the recovery of Lake sturgeon (*Acipenser fulvescens*) in Lake Michigan. Despite efforts to better understand the population biology and habitat use of remnant Lake sturgeon stocks, little information exists on the quantity, quality, and spatial distribution of habitats for riverine life stages. We applied georeferenced habitat information on substrate, water depth, and stream gradient to a Lake sturgeon habitat suitability index in a geographic information system to produce spatially explicit models of life stage–specific habitat characteristics in the Menominee River, Michigan–Wisconsin; the Peshtigo, Oconto, and lower Fox rivers, Wisconsin; and the Manistique River, Michigan. High-quality Lake sturgeon spawning habitat associated with coarse substrates (≥2.1 mm) and moderate- to high-stream gradients (≥0.6 m/km) comprised 1–6% of the available habitat in each system. Staging habitat characterized by water depths greater that 2 m located near potential spawning habitat comprised an additional 17–41%. However, access to a majority of these habitat types (range 30–100%) by Lake sturgeon from Lake Michigan is currently impeded by dams. High-quality juvenile Lake sturgeon habitat associated with finer substrates, lower stream gradients, and a broad range of water depths (i.e., 0.5–8 m) was relatively ubiquitous throughout each system and comprised 69–100% of the available habitat. Our study suggests that efforts to rehabilitate Lake sturgeon populations should consider providing fish passage and creating supplemental spawning habitat to increase reproductive and recruitment potential.

Key words: ***Acipenser fulvescens*, GIS, habitat enhancement, habitat suitability index, population rehabilitation.**

Introduction

The Lake sturgeon (*Acipenser fulvescens*) is the largest and longest lived fish in Lake Michigan (Kempinger 1996). Lake sturgeon were historically abundant in the basin, with estimates ranging from 2–11 million fish (Hay-Chmielewski & Whelan 1997). However, water quality degradation, overfishing, and the damming of spawning tributaries have resulted in decreased abundance, reduced distribution, and the loss of spawning and nursery habitats (Rochard et al. 1990; Auer 1996). As a result, Lake sturgeon receive legal protection throughout their native distribution (Ferguson & Duckworth 1997).

Interest in the conservation of sturgeon and the development of rehabilitation initiatives in Lake Michigan has increased in recent decades (Auer 1996). Research to understand the biology of Lake sturgeon stocks are ongoing (e.g., Baker 1980; Kempinger 1988; Fortin et al. 1993; Kempinger 1996; Baker & Borgeson 1999; Gunderman & Elliott 2004; Benson et al. 2005) and suggest that many populations will require rehabilitation to maintain or increase abundance. Despite our growing understanding of sturgeon biology, studies of riverine habitat characteristics (i.e., quality, quantity, and distribution) are limited (Benson 2004). Adult Lake sturgeon migrate into moderate- to high-gradient lotic habitats associated with large gravel and cobble substrates for spawning (Scott & Crossman 1973), and larval and juvenile fish remain in river environments during the first year of life utilizing slow-flow habitats with sand substrates (Chiasson et al. 1997; Holtgren & Auer 2004; Benson et al. 2005).

The importance of available riverine spawning and juvenile (i.e., age 0) nursery habitats to the persistence of sturgeon populations has been well established (Buckley & Kynard 1981; Parsley et al. 1993; McCabe & Tracy 1994; Gard 1996; Williot et al. 1997; Paragamian et al. 2001). Adequate habitat is considered one of the major factors limiting the abundance of Lake sturgeon in the Great Lakes (Auer 1999*a*). Therefore, rehabilitation goals for Lake Michigan Lake sturgeon cannot be met without knowledge of the habitat characteristics in its tributaries. The objectives of this study were to (1) determine the

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quantity, quality, and spatial distribution of riverine habitats for spawning adult, staging adult, and juvenile life stages of Lake sturgeon in five Lake Michigan tributaries and (2) use this information to determine the most appropriate rehabilitation strategies in each system.

Methods

Study Sites

We selected the Menominee River, Michigan–Wisconsin; the Peshtigo, Oconto, and lower Fox rivers, Wisconsin; and the Manistique River, Michigan, for assessment of Lake sturgeon habitat (Fig. 1). These tributaries support remnant Lake sturgeon populations ranging from less than 10 to approximately 200 spawning adults per year (Zollweg et al. 2003; Schneeberger et al. 2005) and represent a variety of river fragmentation and watershed development conditions ranging from low levels of urbanization and fragmentation (e.g., the Manistique River, <5% urbanization and two dams; Madison & Lockwood 2004) to highly developed and fragmented systems (e.g., the lower Fox River, >70% urbanized and 14 dams; Santy 2001; Table 1).

Field Data Collection

We conducted habitat assessments upstream and downstream of existing barriers in each river from June through August 2004 and 2005. Tributaries were sampled from Lake Michigan to the most upstream Lake sturgeon spawning location based on historic records (P. Cochran, St. Mary's University, Winona, MN, personal communication). Characterization of stream habitats was accomplished following a stratified random sampling design. We divided sampling reaches within each tributary into generalized channel units (i.e., areas of homogenous water depth, water velocity, and substrate characteristics; Armantrout 1998) based on field measures at each transect. Stream channel units were defined as: runs (water depths between 0.5 and 1.0 m in depth and velocities less than 0.3 m/s), riffles (water depths less than 0.5 m and velocities greater than 0.3 m/s), and pools (areas greater than 1.0 m in depth and velocities less than 0.3 m/s).

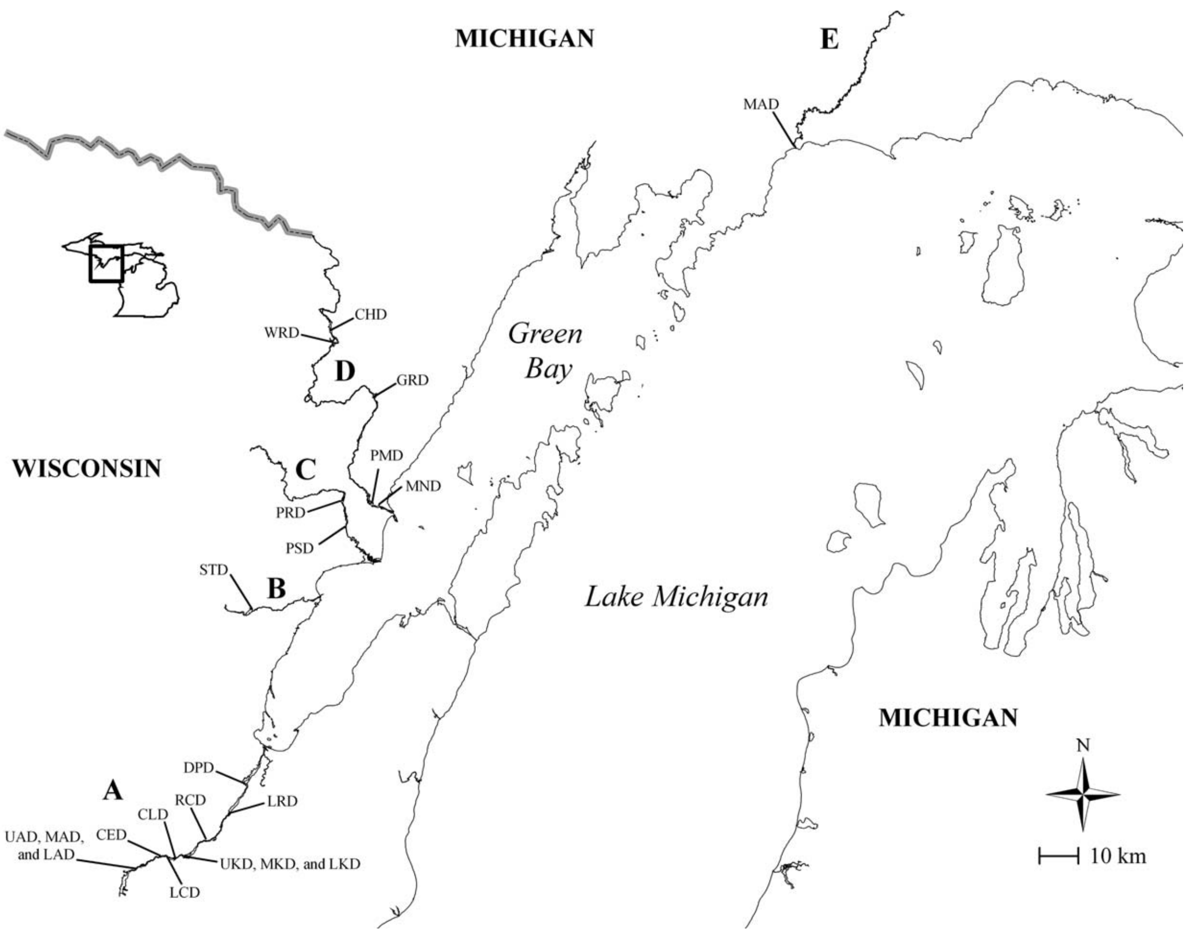

Figure 1. Map of the study region illustrating the location of study systems and dams within each study reach. Letters correspond to rivers as follows: (A) Lower Fox, (B) Oconto, (C) Peshtigo, (D) Menominee, and (E) Manistique. Acronyms refer to the names of dams found in Table 4.

Table 1. Summary statistics of river and watershed characteristics.

River	*Mean Annual Discharge (m^3/s)*	*Watershed Area (km^2)*	*Spawners*	*Historic Range (km)*	*Dams*	*Current Range (km)*	*Impounded Populations*
Menominee	113	10,541	200	132.5	5	4.3	Yes
Peshtigo	24	2,991	200	82	2	19	No
Oconto	16.5	509	30	32.5	1	22.5	No
Fox	116	16,000	<100	64	13	7	Yes
Manistique	42	3,810	<10	98	2	1.1	No

"Historic range" refers to the maximum upstream migration potential of Lake sturgeon *Acipenser fulvescens* based on historical records, "Spawners" refers to the estimated number of spawning adult Lake sturgeon that migrate into the river from Lake Michigan on an annual basis, "Dams" refers to the number of dams found throughout the historic range, and "Current range" refers to the present upstream migration potential.

Within each channel unit, we collected data on substrate composition, water depth, and water velocity from three equidistant point locations along randomly spaced transects perpendicular to stream flow. Additional point samples were collected along transects delineating the upstream and downstream boundaries of each channel unit. Because run habitats typically comprise a majority of low-velocity streams (Hynes 1970), transects were spaced at random intervals between 100 and 200 m. Pools and riffles were sampled at 10- to 50-m intervals to provide more detailed characterization of these habitat types. The geographic coordinates of each sample location were recorded using a wide-angle augmentation system enabled global positioning system receiver (estimated positional accuracy <3 m), and water depth was measured to the nearest 0.1 m using a sonar unit. Because Lake sturgeon are benthivorous (Scott & Crossman 1973), water velocity at each location was measured to the nearest 0.1 m/s approximately 0.3 m above the river bottom using a mechanical flow meter (Model 2030; General Oceanics, Miami, FL, U.S.A.). To increase sampling efficiency, substrate at each location was sampled using a 2.5-cm-diameter aluminum wading pole (3 m in length) in wadeable areas as described by Hamilton and Bergersen (1984), whereas a petite ponar grab sampler was used at water depths greater than 3 m. Substrate type was determined based on median particle size as defined by Threader et al. (1998; Table 2). All habitat data were collected during average summer flow conditions defined by U.S. Geological Survey gauging station data.

Although water depth and flow rate data collected during summer flows represent river habitats experienced by juvenile life stages of Lake sturgeon, these data are not representative of conditions experienced by spawning adults. Spawning occurs from March through May (Scott & Crossman 1973; Auer 1999*b*) and coincides with greater discharge levels caused by spring snowmelt and precipitation events. Therefore, data collected during summer will underestimate the spring water depths and flow rates experienced by spawning adults. Although water depth is of relatively little importance during spawning (0.6–5 m, Scott & Crossman 1973; up to 18 m, Threader et al. 1998; and up to 11 m, Caswell et al. 2004), water velocity is an important criterion for spawning site selection (LaHaye et al. 1992). As a result, stream channel slope, which remains constant regardless of temporal changes in discharge, was calculated as a measure of stream flow potential using Manning's equation:

$$S = \left(\frac{U}{\left(\frac{1}{n}\right)(R_{\mathrm{h}})^{2/3}} \right)^2$$

where S is stream channel slope (m/m), U is water velocity, n is Manning's coefficient, and R_{h} is the hydraulic radius (m) (Chaudhry 1993). Hydraulic radius and Manning's coefficient were estimated using stream width and water depth measurements and the dominant substrate type recorded at each transect, respectively (Table 2; Chaudhry 1993).

Habitat Modeling

Spatially explicit models of each habitat variable were constructed using ArcGIS® 9.1 (Environmental Systems Research Institute [ESRI], Redlands, CA, U.S.A.). Base layers delineating channel features (e.g., boundaries and islands) for each river and reach were digitized using aerial photographs, and the point-sample habitat data from each sampling reach were plotted. We then used interpolation to create raster data models (i.e., spatially explicit, grid-based data) for each habitat variable and

Table 2. Substrate particle-size statistics as reported by Threader et al. (1998) and Manning's n coefficients as reported by Chaudhry (1993) utilized in substrate and stream channel slope interpolation models.

Substrate Class	*Particle Size Range (mm)*	*Median Particle Size (mm)*	*Manning's n Coefficient*
Clay	—	0	0.022
Silt	<1	0.5	0.022
Sand	1–2	1.5	0.022
Gravel	2.1–80	41.1	0.025
Cobble	81–250	166.5	0.035
Boulder	>250	250	0.035
Bedrock	—	500	0.022

sampling reach using the inverse distance weighted method (Bolstad 2002). The polygon base layer for each sampled reach was used as the analysis mask and analysis extent, and the interpolation was parameterized using a variable search radius with four nearest neighbors, a power of 0.5 and cell size of 5 m^2. A power of 0.5 was used to minimize the local influence of nearest neighbor sampling points and create a smooth raster surface (Bolstad 2002). In reaches containing islands or where a highly sinuous or braided channel was present, a polyline barrier layer was created and utilized to prevent the interpolation of neighboring points across land (Rubec et al. 1999). Assessment of modeling accuracy for each habitat variable was accomplished by comparing predicted cell values to randomly collected test datasets in pool, riffle, and run channel units (Daugherty 2006). Mean water depth errors were less than 0.5 m, whereas mean water velocity error was less than 0.1 m/s. Mean error associated with the prediction of median substrate particle size ranged up to 9.3 mm in runs, 21.3 mm in riffles, and 42.1 mm in pool habitats.

Lake Sturgeon Habitat Suitability Modeling

The models of each habitat variable were reclassified into habitat suitability index (HSI) values for each riverine life stage (i.e., staging adult, spawning adult, and juvenile) based on suitability criteria developed by Threader et al. (1998; Table 3). Because HSI models have not been developed for all habitat variables and life stages examined in this study (i.e., stream gradient and staging adult life stage), habitat suitability criteria were developed based on a review of the available literature and scaled as defined above (Table 3). We then calculated the geometric mean of the reclassified models for each habitat variable and life stage to provide a composite model of habitat suitability throughout each study reach (Li et al. 1984; Threader et al. 1998; Rubec et al. 1999). Cells of the composite model with a value of 0 were defined as unsuitable habitat, whereas cell values ranging between 0 and 0.79 were defined as marginal habitat (Threader et al. 1998). Raster cells in the composite models with a value between 0.8 and 1 were considered to provide high-quality habitat for the respective life stage. Because previous studies have indicated that some habitat characteristics do not appear to be limiting factors for certain life stages of Lake sturgeon, not all habitat variables measured during this study were utilized to model habitat suitability for all life stages (Table 3).

Areas within each suitability model representing unsuitable habitat were omitted using a select-by-attribute routine (ESRI 2005). Additional select-by-attribute and select-by-location routines were performed on juvenile and staging adult suitability models to meet geometric or geographic (i.e., patch size or locational, respectively) habitat requirements as suggested by Benson et al. (2005) for juveniles and McKinley et al. (1998) and Bruch and Binkowski (2002) for staging adults (Table 3). To assess the ability of the models to accurately identify Lake sturgeon habitat, we qualitatively compared known spawning adult and juvenile capture locations based on previous research in each river to the predicted habitat models. Habitats in each river system known to be utilized by each life stage of Lake sturgeon were correctly identified as high-quality habitat.

Data Analyses

The life stage–specific habitat suitability models were used to determine the total availability, relative availability, spatial distribution, habitat patch size distribution, and quality characteristics of Lake sturgeon habitat within each system. Raster models of habitat suitability for each life stage, sampling reach, and system were converted to polygon feature classes, and the total area (m^2) of all habitat patches was calculated. The resulting information was then used in context with reported information on the status of Lake sturgeon in these tributaries to determine the most appropriate rehabilitation strategies in each system.

Results

Menominee River

A total of 2,005 habitat samples were collected in the Menominee River during July 2004 (Table 4). Models indicated that high-quality Lake sturgeon spawning habitat accounted for 4.5% of the study reach (Table 5). An additional 40% of the habitat was classified as marginal. Greater than 90% of the high-quality spawning habitat in the Menominee River was distributed throughout the impounded reaches and unavailable to spawning Lake sturgeon from Lake Michigan (Table 5). The majority (87%) of this habitat was located in the river reaches impounded by the Park Mill (22%), Grand Rapids (38%), and Chalk Hill (27%) dams (Fig. 1; Table 5). Staging habitat was relatively ubiquitous throughout the study reach and comprised 46% of the available habitat (Table 6). Models characterizing juvenile habitat indicated that 82% of the Menominee River provided high-quality habitat (Table 7). However, only 4% of the high-quality juvenile Lake sturgeon habitat was accessible to Lake Michigan Lake sturgeon.

Peshtigo River

Analysis of 3,245 habitat samples collected in the Peshtigo River during June 2004 indicated that 4% of the river provided high-quality Lake sturgeon spawning habitat. However, access to greater than 97% of this habitat from Lake Michigan was blocked by the Peshtigo and Potato Rapids Dams (Fig. 1; Table 5). Staging habitat in the free-flowing reach was limited (<0.01% of the free-flowing reach) and associated with marginal spawning habitat. Staging habitat found throughout the impounded reaches was associated with areas of high-quality spawning habitat (Table 6). High-quality juvenile Lake sturgeon habitat in the

Table 3. Input values for the identification of optimal, marginal, and unsuitable habitats for riverine life stages of Lake sturgeon (*Acipenser fulvescens*).

Life Stage	*Habitat Variable*	*Suitability Index*	*Source*
Egg/spawning adult			
	Substrate		
	Clay	0	Threader et al. (1998)
	Silt	0	Threader et al. (1998)
	Sand	0	Threader et al. (1998)
	Gravel	0.5	Threader et al. (1998)
	Cobble	1	Threader et al. (1998)
	Boulder	1	Threader et al. (1998)
	Bedrock	0.3	Threader et al. (1998)
	Stream gradient (m/km)		
	>1.0	1	Hay-Chmielewski and Whelan (1997)
	0.6–1.0	1	Hay-Chmielewski and Whelan (1997)
	0.3–0.59	0.5	Hay-Chmielewski and Whelan (1997)
	0.0	0	Hay-Chmielewski and Whelan (1997)
Larval/juvenile			
	Substrate composition		
	Clay	0.2	Threader et al. (1998)
	Silt	1	Threader et al. (1998)
	Sand	1	Threader et al. (1998)
	Gravel	1	Threader et al. (1998)
	Cobble	0.8	Threader et al. (1998)
	Boulder	0.5	Threader et al. (1998)
	Bedrock	0.2	Threader et al. (1998)
	Stream gradient (m/km)		
	>1.0	0	Benson et al. (2005)
	0.6–1.0	1	Benson et al. (2005)
	0.3–0.59	0.9	Benson et al. (2005)
	0.0	0.5	Benson et al. (2005)
	Water depth (m)		
	<0.5	0	Threader et al. (1998)
	0.5–1.9	0.8	Threader et al. (1998)
	2.0–4.0	0.9	Threader et al. (1998)
	4.0–7.9	1	Threader et al. (1998)
	8.0–14.0	0.5	Threader et al. (1998)
	>14.0	0	Threader et al. (1998)
	Geographic constraint		
	>0.5 rkm of habitat	1	Benson et al. (2005)
	<0.5 rkm of habitat	0.9	Benson et al. (2005)
Staging adult			
	Water depth (m)		
	<2.0 m	0	Bruch and Binkowski (2002)
	>2.0 m	1	McKinley et al. (1998); Bruch and Binkowski (2002)
	Geographic constraint		
	<3 km from potential spawning habitat	1	Bruch and Binkowski (2002)
	>3 km from potential spawning habitat	0	Bruch and Binkowski (2002)

Suitability index value of 0 refers to unsuitable habitats, whereas values ranging between 0 and 0.79 were defined as marginal habitat. Values of 0.8–1 were considered to provide high-quality habitat.

Peshtigo River was relatively ubiquitous and comprised greater than 94% of the available habitat (Table 7).

Oconto River

Models based on the collection of 647 habitat samples in the Oconto River during June 2005 indicated that 6% of the river provides high-quality Lake sturgeon spawning habitat (Table 5). Eleven percent of this habitat was accessible to Lake sturgeon in the free-flowing reach. The remaining 89% is located above the Stiles Dam site (Fig. 1). Staging habitat in the free-flowing reach of the Oconto River was limited (0.3% of the available habitat). Staging habitat in the impounded reach comprised 81% of the available habitat due to the relatively short length of the reach (9.3 river kilometers [rkm]) and the impoundment created by the dam. Ninety-nine percent of the available habitat in the Oconto River was

Table 4. Habitat sample sizes collected in each river during June to August 2004 to 2005.

River and Reach	*Reach Length (km)*	*Number of Point Samples*
Menominee		
Free flowing	4	63
Menominee Dam(MND)	2.1	30
Park Mill Dam (PMD)	31.2	449
Grand Rapids Dam (GRD)	43.8	745
White Rapids Dam (WRD)	35.1	156
Chalk Hill Dam (CHD)	26.7	562
Total	142.9	2,005
Peshtigo		
Free flowing	19.1	2,130
Peshtigo Dam (PSD)	7	142
Potato Rapids Dam (PRD)	41.2	973
Total	67.3	3,245
Oconto		
Free flowing	22.5	497
Stiles Dam (STD)	10	150
Total	32.5	647
Fox		
Free flowing	11.3	102
DePere Dam (DPD)	7	120
Little Rapids Dam (LRD)	7.2	135
Rapide Croche Dam (RCD)	4	100
Lower Kaukauna Dam (LKD)	1.1	155
Middle Kaukauna Dam (MKD)	2.1	60
Upper Kaukauna Dam (UKD)	1.5	25
Combined Locks Dam (CLD)	1.3	25
Little Chute Dam (LCD)	1.9	30
Cedars Dam (CED)	4.6	65
Lower Appleton Dam (LAD)	1	25
Middle Appleton Dam (MAD)	0.5	33
Upper Appleton Dam (UAD)	6.5	101
Total	50	976
Manistique		
Free flowing	1.1	33
Manistique Dam	96.5	2,230
Total	97.6	2,263

Reach names are based on the impounding dam.

classified as high-quality juvenile Lake sturgeon habitat (Table 7).

Lower Fox River

Habitat suitability models in the lower Fox River were constructed based on 976 habitat samples collected during June 2005 (Table 4). Similar to the other systems examined in this study, high-quality spawning habitat accounted for 4% of the total habitat available throughout the study reach (Table 5). Sixteen percent of the high-quality spawning habitat was available to Lake sturgeon from Lake Michigan, whereas the majority (58%) of the highly suitable spawning habitat was found in the reaches impounded by the Rapide Croche (36%) and lower Kaukauna (17%) dams (Fig. 1; Table 5). Staging habitat was relatively ubiquitous throughout the study reach and comprised 39% of the available habitat. Greater than 99% of the available habitat in the lower Fox River was classified as high-quality juvenile habitat (Table 7).

Manistique River

A total of 2,263 habitat samples were collected from the Manistique River during August 2005 (Table 4). High-quality spawning habitat was limited in the Manistique River, with less than 1% of the study reach classified as high-quality spawning habitat (Table 5). In contrast to the other river systems examined in this study, a majority (70%) of the high-quality spawning habitat was accessible to Lake sturgeon migrating the river from Lake Michigan. The remaining 30% was distributed among small (<3,000 m^2) patches of highly suitable spawning habitat in the impounded reach (Table 5). Staging habitat in the free-flowing and impounded reaches comprised 51 and 15% of the available habitat, respectively. High-quality juvenile Lake sturgeon habitat comprised 69% of the free-flowing reach, whereas 99% of the available habitat in the impounded reach was classified as high-quality juvenile habitat (Table 7).

Discussion

A lack of available, high-quality habitat for riverine life stages of sturgeons are known to contribute to limited or failed recruitment (Khoroshko 1972; Parsley et al. 1993; Williot et al. 1997; Paragamian et al. 2001; Jager et al. 2002). Anthropogenic activities in Lake Michigan during the past two centuries have influenced the recruitment success and resulting population size of Lake sturgeon by eliminating access to spawning habitats through the placement of dams and the development of nutrient-rich river mouths important for juvenile fish (Auer 1999*a*). The habitat models developed for the rivers examined in this study support these results and suggest that the quantity, quality, and distribution of habitats for all riverine life stages are important considerations in determining Lake sturgeon rehabilitation strategies.

Menominee River

The long-term goal of Lake sturgeon management in the Menominee River is to provide free passage throughout their historical range (Thuemler 1997). The habitat models developed for the Menominee River suggest that fish passage, either through the installation of passage structures or dam removal, may be an appropriate strategy for rehabilitating Lake sturgeon. The large proportion (60%) of high-quality spawning habitat identified in the river reaches impounded by the Park Mill, Grand Rapids, and Chalk Hill dams would result in a 90% increase in spawning habitat available to Lake sturgeon from Lake Michigan and allow for the emigration and immigration of individuals throughout the system.

Table 5. Summary statistics of high-quality spawning habitat for Lake sturgeon (*Acipenser fulvescens*) in each river and reach.

River and Reach	*Spawning Habitat (m^2)*	*Patch size Range (m^2)*	*Total Availability (%)*	*Relative Availability (%)*
Menominee				
Free flowing	104,396		9.9	9.8
Menominee Dam	2,183	935–1,247	0.4	0.4
Park Mill Dam	234,025	17–130,410	3.6	22.1
Grand Rapids Dam	405,283	17–152,539	5.7	38.3
White Rapids Dam	27,253		1.5	2.5
Chalk Hill Dam	285,550	17–108,821	4.3	26.9
Total	1,058,690		4.5	
Peshtigo				
Free flowing	8,661		0.4	2.7
Peshtigo Dam	144,467		10.2	45.7
Potato Rapids Dam	162,753	17–48,482	4.4	51.5
Total	315,881		4.3	
Oconto				
Free flowing	25,589	17–13,241	1.5	11.1
Stiles Dam	203,774	77,267–126,507	9	88.9
Total	229,363		5.8	
Fox				
Free flowing	152,089		2.7	15.7
DePere Dam	0		0	0
Little Rapids Dam	10,574		0.6	1.1
Rapide Croche Dam	349,468		15.3	36.2
Lower Kaukauna Dam	154,319	17–54,319	99.4	17.6
Middle Kaukauna Dam	51,440		99.1	3.7
Upper Kaukauna Dam	116		0.02	0.01
Combined Locks Dam	0		0	0
Little Chute Dam	20,318		1.8	2
Cedars Dam	36,569	17–20,301	17.9	3.4
Lower Appleton Dam	50,415		99.8	5.3
Middle Appleton Dam	72,550		99.9	7.3
Upper Appleton Dam	75,338		1.3	7.7
Total	973,196		4.4	
Manistique				
Free flowing	20,270		6.3	70
Manistique Dam	8,678	17–2,236	0.2	30
Total	28,948		0.6	

Total availability refers to the percent availability of high-quality spawning habitat within the respective river reach. Relative availability refers to the percent availability of high-quality spawning habitat within the reach relative to the system.

Peshtigo River

Rehabilitation objectives for Lake sturgeon in Wisconsin tributaries of Lake Michigan include the maintenance and enhancement of remnant stocks and the reestablishment of populations throughout their former range (Wisconsin Department of Natural Resources [WDNR] 2004). Historically, Lake sturgeon were considered to have been distributed throughout the lower 67 km of the Peshtigo River (T. Meronek, WDNR, personal communication). However, Lake sturgeon are currently limited to the free-flowing reach. Although this reach supports a sizeable remnant population, analyses of our habitat models suggest that the Peshtigo River has the potential to support a much larger population. The river reaches impounded by the Peshtigo and Potato Rapids Dams contain approximately 95% of the high-quality spawning habitat and 75% of the high-quality juvenile habitat present in the system. Therefore, providing access to these reaches through fish passage may serve to increase the carrying capacity of Lake sturgeon in the Peshtigo River and return the species to its native range.

Oconto River

The results of our study suggest that habitat for riverine life stages of Lake sturgeon may not limit abundance in this system. The availability of high-quality spawning and staging habitat in the free-flowing reach of the Oconto River is approximately 70 and 90% greater, respectively, than that of the free-flowing reach of the Peshtigo River, with similar quantities of juvenile habitat present in each tributary. However, the Oconto River currently supports approximately 95% fewer spawners than the Peshtigo River. These results suggest that other factors may be contributing to the limited abundance of Lake sturgeon in this system.

Table 6. Summary statistics of high-quality adult staging habitat for Lake sturgeon (*Acipenser fulvescens*) in each river and reach.

River and Reach	*Spawning Habitat* (m^2)	*Patch Size Range* (m^2)	*Total Availability (%)*	*Relative Availability (%)*
Menominee				
Free flowing	744,884	17–675,099	71	6.6
Menominee Dam	394,388	25–394,216	73.1	3.5
Park Mill Dam	3,217,165	17–2,133,910	48.9	28.6
Grand Rapids Dam	1,944,086	17–825,594	27.3	17.3
White Rapids Dam	1,802,610	17–1,802,539	99	16
Chalk Hill Dam	3,151,666	17–2,501	48.1	28
Total	11,254,799		46	
Peshtigo				
Free flowing	560	17–225	0.02	0.1
Peshtigo Dam	701,218	17–461,005	49.5	55.4
Potato Rapids Dam	562,819	17–467,481	15.1	44.5
Total	1,264,597		32	
Oconto				
Free flowing	4,571	17–2,419	0.3	0.3
Stiles Dam	1,831,217	17–1,831,860	80.9	99.7
Total	1,835,788		46.9	
Fox				
Free flowing	2,086,018	25–2,080,600	38.3	23.2
DePere Dam	2,189,361	17–1,179,635	57.9	24.4
Little Rapids Dam	1,360,132	17–1,323,563	73	15.1
Rapide Croche Dam	0		0	0.0
Lower Kaukauna Dam	205,759	17–54,319	99.9	2.3
Middle Kaukauna Dam	154,319		99.1	1.7
Upper Kaukauna Dam	315,926	17–315,909	60.6	3.5
Combined Locks Dam	211,212		54.6	2.3
Little Chute Dam	158,341	17–158,175	48.1	1.8
Cedars Dam	975,076	50–974,752	86.2	10.8
Lower Appleton Dam	411	17–376	0.2	>0.1
Middle Appleton Dam	0		0	0.0
Upper Appleton Dam	1,334,056	17–1,312,453	23.3	14.8
Total	8,990,611		39	
Manistique				
Free flowing	164,833	25–162,651	51.1	20.4
Manistique Dam	646,159	17–204,335	14.8	79.6
Total	810,992		17.3	

Total availability refers to the percent availability of high-quality staging habitat within the respective river reach. Relative availability refers to the percent availability of high-quality staging habitat within the reach relative to the system.

Historically, pollution from paper mill effluents significantly impacted water quality in the Oconto River (M. Donofrio, WDNR, personal communication), and illegal harvest of spawning adult Lake sturgeon at the Stiles Dam is known to have occurred. Over time, these factors may have negatively affected adult spawning stock abundance. Due to the unique life history characteristics of Lake sturgeon (i.e., late age at maturity, periodic spawning strategy, and low recruitment), recovery of the adult spawning stock may not have been realized to date. In addition, the free-flowing reach of the Oconto River primarily supports a cold water fishery, whereas the Peshtigo River supports species associated with cool-water environments (WDNR 2002). Although little information currently exists on the impact of various fish community dynamics (e.g., predation, competition) on survival and recruitment of early life stages of Lake sturgeon (Zollweg et al. 2003), these differences may contribute to the low population abundance. As a result, rehabilitation strategies in the Oconto River focused on increasing spawner abundance and determining factors currently limiting recruitment should be considered. Development of a stocking or streamside rearing program in the Oconto River may increase recruitment and adult spawner abundance (Lake Michigan Lake Sturgeon Task Group 2005). The stocking of various early life stages (e.g., larvae, age 0, and age 1 juveniles) may also provide an opportunity to determine where potential recruitment bottlenecks exist in the system.

Fox River

Spawning by Lake sturgeon in the lower Fox River is known to occur in the free-flowing reach (< 100 spawning adults per year), with occasional observations of adult fish in the impounded reaches (Cochran 1995; Gunderman & Elliott 2004). Similar to our observations regarding the

Table 7. Summary statistics of high-quality juvenile habitat for Lake sturgeon (*Acipenser fulvescens*) in each river and reach.

River and Reach	*Juvenile Habitat (m^2)*	*Patch Size Range (m^2)*	*Total Availability (%)*	*Relative Availability (%)*
Menominee				
Free flowing	858,063	17–788,020	81.9	4.4
Menominee Dam	538,325		99.8	2.8
Park Mill Dam	6,514,534	17–6,458,899	99.1	33.7
Grand Rapids Dam	6,449,789	25–6,443,779	90.6	33.4
White Rapids Dam	1,819,932	17–1,488,758	99.9	9.4
Chalk Hill Dam	4,624,718	17–2,396,882	70.6	23.9
Total	19,316,586		81.7	
Peshtigo				
Free flowing	1,749,467	17–903,660	81.2	25.5
Peshtigo Dam	1,405,589	17–1,405,371	99.3	20.4
Potato Rapids Dam	3,718,856	17–421,542	99.8	54.1
Total	6,873,912		94.2	
Oconto				
Free flowing	1,690,652	1,239–1,689,412	100	43.2
Stiles Dam	2,221,371	16–2,171,223	98.1	56.8
Total	3,912,023		98.9	
Fox				
Free flowing	5,411,942	17–5,405,077	99	24.4
DePere Dam	3,775,361		99	17.0
Little Rapids Dam	1,860,048	17–1,853,978	100	8.4
Rapide Croche Dam	2,134,426	17–2,116,146	93.2	9.6
Lower Kaukauna Dam	205,758	17–201,065	99.9	0.9
Middle Kaukauna Dam	520,907	17–519,570	100	2.3
Upper Kaukauna Dam	512,679	25–512,352	97.7	2.3
Combined Locks Dam	329,222		100	1.5
Little Chute Dam	1,136,017	273–1,135,743	100	5.1
Cedars Dam	204,385		100	0.9
Lower Appleton Dam	250,426	17–89,990	99.7	1.1
Middle Appleton Dam	122,015	25–121,957	99	0.6
Upper Appleton Dam	5,720,922	33–5,720,889	100	25.8
Total	22,184,108		99.9	
Manistique				
Free flowing	221,451		68.7	4.8
Manistique Dam	4,365,256	17–2,881,545	99.9	95.2
Total	4,583,707		97.7	

Total availability refers to the percent availability of high-quality juvenile habitat within the respective river reach. Relative availability refers to the percent availability of high-quality juvenile habitat within the reach relative to the system.

relationship between habitat availability and Lake sturgeon population abundance in the free-flowing reaches of the Oconto and Peshtigo rivers, a comparison of the lower Fox River to the free-flowing reach of the Menominee River suggests that factors other than limited habitat availability may be important in explaining the current stock size of Lake sturgeon in this reach. The availability of high-quality spawning and staging habitats in the free-flowing reach of the lower Fox River is 30 and 65% greater, respectively, than that found in the Menominee River. The lower Fox River also provides 85% more juvenile habitat. However, spawner abundance in the lower Fox River is estimated to be less than half of that found in the free-flowing reach of the Menominee River. The observations of greater Lake sturgeon habitat availability, combined with a larger size (estimated surface areas; lower Fox = 5.6×10^6 m^2; Menominee = 1.1×10^6 m^2; this study), suggests that the free-flowing reach of the lower Fox River should have the capacity to support a significantly larger Lake sturgeon population.

Potential factors limiting Lake sturgeon abundance in the lower Fox River may be related to historical environmental degradation, poor water quality, and an altered flow regime (Harris et al. 1987; Cochran 1995; Gunderman & Elliott 2004). Polychlorinated biphenyl contamination resulted in dramatic declines in invertebrate species richness and the loss of the Burrowing mayfly (*Hexagenia bilineata*) from this system (Schneider et al. 1991; Cochran 1992, 1995). The loss of these food items for juvenile Lake sturgeon, as well as the potential direct impacts of pollution on early life history stages (Bennett & Farrell 1998; Doyon et al. 1999), may have been and continue to be important factors limiting Lake sturgeon recruitment. Altered discharge regimes, utilized to maintain water levels in upstream impoundments or for hydropower generation, have resulted in the occasional dewatering of Lake sturgeon spawning habitat in the free-flowing reach during egg deposition and incubation periods which may also negatively affect reproductive success. Although water quality improvements, reduced contaminant inputs, and the partial removal of contaminated sediments from the lower Fox River have increased invertebrate and fish species richness over the past two decades (Schneider et al. 1991; Cochran 1995), remaining contaminants and water management practices remain a concern. Therefore, Lake sturgeon rehabilitation efforts in the lower Fox River should focus on maximizing the suitability of accessible habitat and increasing Lake sturgeon abundance in the free-flowing reach before attempts to reestablish this species throughout the system are initiated. The development of a stocking program, coupled with water management practices that maintain suitable Lake sturgeon habitat during critical periods, would be an appropriate rehabilitation strategy in this reach. Based on the habitat models developed in our study, longer-term Lake sturgeon rehabilitation goals should consider fish passage. Providing access to the river reaches impounded by the Rapide Croche and Lower Kaukauna dams would increase spawning habitat availability by 70% and juvenile habitat availability by 53%.

Manistique River

Lake sturgeon spawner abundance in the Manistique River is estimated at less than 10 fish per year, and successful spawning has not been documented (Zollweg et al. 2003). Although little information exists on the historical abundance of Lake sturgeon in the Manistique River (Madison & Lockwood 2004), abundance and reproductive success may be limited by the length of the free-flowing reach. The Manistique Dam is located 1.1 rkm from the mouth of the river at Lake Michigan, creating one of the shortest free-flowing reaches in the Lake Michigan basin (Auer 1996). Gonadal maturation in fishes often occurs during spawning migrations (McKeown 1984; Auer 1996), and female sturgeons may fail to spawn or egg survival may be reduced if migration routes to upstream spawning locations are impeded (Artyukhin et al. 1978; Veshchev & Novikova 1988). The relatively short free-flowing reach may also negatively affect the development, growth, and survival of larval fish. Lake sturgeon are known to passively drift downstream following the onset of exogenous feeding (Kempinger 1988), which facilitates transport of larval fish to lower river reaches associated with nutrient-rich sediments, diverse invertebrate communities, and lower current velocities (Brannon et al. 1985; Auer & Baker 2002; Parsley et al. 2002). The short reach length and low availability of high-quality juvenile habitat in the free-flowing reach of the Manistique River may result in the displacement of larval Lake sturgeon into the Lake Michigan basin. Although successful spawning is supported in the free-flowing reach of the Menominee River, which is similar in length (4.3 km), this tributary contains approximately 75% more high-quality juvenile habitat and discharges into Green Bay, which provides additional, nutrient-rich nursery habitat for early life history stages (Benson 2004). Despite their similar reach lengths, the differences in early life stage habitat availability and their geographic relationship with the lake environment may explain the apparent lack of reproductive success in the Manistique River.

Providing fish passage may be an appropriate rehabilitation strategy in the Manistique River. This strategy would provide access to an additional 96.5 km of riverine habitat and increase juvenile habitat availability by 95%. However, this option would fail to provide additional spawning habitat. High-quality spawning habitat in the reach currently upstream of the Manistique Dam is highly limited and represents less than 1% of the available habitat. Therefore, although the capacity of the Manistique River to support larval and juvenile Lake sturgeon production would greatly increase, the availability of spawning habitat would likely continue to limit Lake sturgeon production. A combination of spawning habitat enhancement and fish passage may be necessary to increase the production of Lake sturgeon in the Manistique River.

Conclusions

Conserving Lake sturgeon in the Lake Michigan basin will aid in the maintenance of biological integrity and species diversity in the Great Lakes. However, the unique life history of this species creates a complex framework for rehabilitating remnant populations. The results of our study suggest that system-specific assessments of Lake sturgeon habitat characteristics are required to aid in the determination of the most appropriate rehabilitation strategies in each system. However, the sociocultural, economic, political, and ecological implications of these strategies must also be considered (Born et al. 1998). Management approaches that favor the rehabilitation of one species often negatively affect the management of others (Ryan et al. 2003). For example, dams that currently impede Lake sturgeon access to spawning and nursery habitats in upper river reaches also function to block spawning migrations of the non-native Sea lamprey (*Petromyzon marinus*) (Lavis et al. 2003). Providing access to upstream reaches for Lake sturgeon, either through the construction of fish passage structures or dam removal, would likely result in improved conditions for Lake sturgeon rehabilitation (i.e., increased habitat) and negative consequences for Sea lamprey control efforts. Dam removal may negatively affect publicly desirable reservoir fisheries and recreational use patterns and result in disturbances to downstream aquatic communities due to temporarily increased sediment loads (Bednarek 2001) or unpredictable changes in river morphology (Pizzuto 2002). Toxicants in sediments contained above dams may also be redistributed throughout the system (Bednarek 2001), and contaminated fish limited to downstream reaches may act as transport mechanisms to introduce these chemicals to upstream food webs (Freeman et al. 2002). Therefore, Lake sturgeon rehabilitation strategies should be implemented as part of an integrated, multiscale approach to Lake Michigan fishery management.

Although this study provides a critical first step in understanding the current and potential ability of these rivers to support Lake sturgeon spawning and recruitment, additional research is required to further define the biological and ecological mechanisms that impact populations at all life history stages. Research aimed at understanding Lake sturgeon habitat use at both smaller (e.g., microhabitat) and larger (e.g., watershed) geographic scales, determination of life stage–specific minimum habitat areas, and the influence of habitat patch dynamics and spatial ecology are needed to provide a better understanding of Lake sturgeon habitat. The results of such studies should be incorporated into future evaluations of Lake sturgeon habitat suitability in order to further facilitate the successful rehabilitation of Lake sturgeon in Lake Michigan.

Implications for Practice

- The utilization of a Lake sturgeon HSI in a geographic information system (GIS) provides a standardized, spatially explicit method for assessing life stage–specific Lake sturgeon habitat characteristics. This technique could be applied to Lake sturgeon habitat assessment efforts in other Lake Michigan tributaries.
- Differences in life stage–specific Lake sturgeon habitat availability and corresponding Lake sturgeon population abundance among the tributaries examined in this study illustrate the importance of system-specific Lake sturgeon habitat and population assessments. This information is critical to the determination of the most appropriate rehabilitation strategy in a candidate system.
- Decisions regarding the rehabilitation of Lake sturgeon populations should be considered as part of an integrated, multiscale approach to fisheries management in Lake Michigan. In particular, rehabilitation approaches involving the provision of fish passage should consider the effects on other species prior to implementation.
- Additional investigations of Lake sturgeon habitat selection are required to further refine habitat suitability criteria for this species. The results of such investigations should be incorporated in the future determinations of Lake sturgeon habitat characteristics in Lake Michigan tributaries.

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LITERATURE CITED

Armantrout, N. B., compiler. 1998. Glossary of aquatic habitat inventory terminology. American Fisheries Society, Bethesda, Maryland.

Artyukhin, E. N., A. D., Sukhoparova, and L. G. Fimukhina. 1978. The gonads of the sturgeon, *Acipenser gueldenstadt*, in the zone below the dam of the Volgrad water engineering system. Journal of Ichthyology **18:**912–923.

Auer, N. A. 1996. Response of spawning lake sturgeons to change in hydroelectric facility operation. Transactions of the American Fisheries Society **125:**66–77.

Auer, N. A. 1999*a*. Lake sturgeon: a unique and imperiled species in the Great Lakes. Pages 515–536 in W. W. Taylor and C. P. Ferreri, editors. Great Lakes fisheries policy and management: a binational perspective. Michigan State University Press, East Lansing.

Auer, N. A. 1999*b*. Population characteristics and movements of lake sturgeon in the Sturgeon River and Lake Superior. Journal of Great Lakes Research **25:**282–293.

Auer, N. A., and E. A. Baker. 2002. Duration and drift of larval lake sturgeon in the Sturgeon River, Michigan. Journal of Applied Ichthyology **18:**557–564.

Baker, E. A., and D. J. Borgeson. 1999. Lake sturgeon abundance and harvest in Black Lake, Michigan, 1975-1999. North American Journal of Fisheries Management **19:**1080–1088.

Baker, J. P. 1980. The distribution, ecology, and management of lake sturgeon (*Acipenser fulvescens* Rafinesque) in Michigan. Fisheries research report 1883, Michigan Department of Natural Resources, Lansing, Michigan.

Bednarek, A. T. 2001. Undamming rivers: a review of the ecological impacts of dam removal. Environmental Management **27:**803–814.

Bennett, W. R., and A. P. Farrell. 1998. Acute toxicity testing with juvenile white sturgeon, *Acipenser transmontanus*. Water Quality Research Journal of Canada **33:**95–110.

Benson, A. C. 2004. Characterization of early life-history stages of lake sturgeon in the lower Peshtigo River, Wisconsin, and nearshore waters of Green Bay. Master's thesis. Purdue University, West Lafayette, Indiana.

Benson, A. C., T. M. Sutton, R. F. Elliott, and T. G. Meronek. 2005. Movement patterns and habitat preferences of age-0 juvenile lake sturgeon in the lower Peshtigo River, Wisconsin. Transactions of the American Fisheries Society **134:**1400–1409.

Bolstad, P. 2002. GIS fundamentals: a first text on geographic information systems. Eider Press, White Bear Lake, Minnesota.

Born, S. M., K. D. Genskow, T. L. Filbert, N. Fernandez-Mora, M. L. Keefer, and K. A. White. 1998. Socioeconomic and institutional dimensions of dam removals: the Wisconsin experience. Environmental Management **22:**359–370.

Brannon, E. S., S. Brewer, A. Setter, M. Miller, F. Utter, and W. Hershberger. 1985. Columbia River white sturgeon early life history and genetics study. Final report (project number 83-316) to the Bonneville Power Administration, Portland, Oregon.

Bruch, R. M., and F. P. Binkowski. 2002. Spawning behavior of lake sturgeon (*Acipenser fulvescens*). Journal of Applied Ichthyology **18:** 570–579.

Buckley, J., and B. Kynard. 1981. Spawning and rearing of shortnose sturgeon from the Connecticut River. Progressive Fish-Culturist **43:** 74–76.

Caswell, N. M., D. L. Peterson, B. A. Manny, and G. W. Kennedy. 2004. Spawning by lake sturgeon (*Acipenser fulvescens*) in the Detroit River. Journal of Applied Ichthyology **20:**1–6.

Chiasson, W. B., D. L. G. Noakes, and F. W. H. Beamish. 1997. Habitat, benthic prey, and distribution of juvenile lake sturgeon (*Acipenser fulvescens*) in northern Ontario rivers. Canadian Journal of Fisheries and Aquatic Sciences **54:**2866–2871.

Chaudhry, M. H. 1993. Open-channel flow. Prentice-Hall Inc., Upper Saddle River, New Jersey.

Cochran, P. A. 1992. The return of *Hexagenia* (Ephemeroptera: Ephemeridae) to the lower Fox River, Wisconsin. Great Lakes Entomologist **25:**79–81.

Cochran, P. A. 1995. Lake sturgeon (*Acipenser fulvescens*) in the lower Fox River, Wisconsin. The Sturgeon Quarterly **3:**8.

Daugherty, D. J. 2006. Development and implementation of habitat availability models to determine lake sturgeon restoration strategies in northern Lake Michigan tributaries. Doctoral dissertation. Purdue University, West Lafayette, Indiana.

Doyon, C., R. Fortin, and P. A. Spear. 1999. Retinoic acid hydroxylation and teratogenesis in lake sturgeon (*Acipenser fulvescens*) from the St. Lawrence River and Abitibi region, Quebec. Canadian Journal of Fisheries and Aquatic Sciences **56:**1428–1436.

ESRI (Environmental Systems Research Institute) 2005. ArcGIS 9.0. ESRI, Redlands, California.

Ferguson, M. M., and G. A. Duckworth. 1997. The status and distribution of the lake sturgeon, *Acipenser fulvescens*, in the Canadian provinces of Manitoba, Ontario and Quebec: a genetic perspective. Environmental Biology of Fishes **48:**299–309.

Fortin, R., J. R. Mongeau, G. Desjardins, and P. Dumont. 1993. Movements and biological statistics of lake sturgeon (*Acipenser fulvescens*) populations from the St. Lawrence and Ottawa River systems. Canadian Journal of Zoology **71:**638–650.

Freeman, R., W. Bowerman, T. Grubb, A. Bath, G. Dawson, K. Ennis, and J. Giesy. 2002. Opening rivers to TROJAN fish: the ecological dilemma of dam removal. Conservation in Practice **3:**35–40.

Gard, M. 1996. Sacramento River white sturgeon spawning criteria. U.S. Fish and Wildlife Service, Sacramento, California.

Gunderman, B. J., and R. F. Elliott. 2004. Assessment of remnant lake sturgeon populations in the Green Bay basin, 2002-2003. Great Lakes Fishery Trust report, project number 2001.113. Great Lakes Fishery Trust, Lansing, Michigan.

Hamilton, K., and E. P. Bergersen. 1984. Methods to estimate aquatic habitat variables. U.S. Bureau of Land Reclamation, Engineering and Research Center, Denver, Colorado.

Harris, H. J., P. E. Sager, C. J. Yarbrough, and H. J. Day. 1987. Evolution of water resource management: a Laurentian Great Lakes case study. International Journal of Environmental Studies **29:**53–70.

Hay-Chmielewski, E. M., and G. Whelan, editors. 1997. Lake sturgeon rehabilitation strategy. Special report 18, Michigan Department of Natural Resources, Fisheries Division, Lansing, Michigan.

Holtgren, J. M., and N. A. Auer. 2004. Movement and habitat use of juvenile lake sturgeon (*Acipenser fulvescens*) in the Sturgeon River/Portage Lake system, Michigan. Journal of Freshwater Ecology **19:**419–432.

Hynes, H. B. N. 1970. The ecology of running waters. The University of Toronto Press, Toronto, Canada.

Jager, H. I., W. Van Winkle, J. A. Chandler, K. B. Lepla, P. Bates, and T. D. Counihan. 2002. A simulation study of factors controlling white sturgeon recruitment in the Snake River. American Fisheries Society Symposium **28:**127–150.

Kempinger, J. J. 1988. Spawning and early life history of lake sturgeon in the Lake Winnebago system, Wisconsin. American Fisheries Society Symposium **5:**110–122.

Kempinger, J. J. 1996. Habitat, growth, and food of young lake sturgeons in the Lake Winnebago system, Wisconsin. North American Journal of Fisheries Management **16:**102–114.

Khoroshko, P. N. 1972. The amount of water in the Volga basin and its effect on the reproduction of sturgeon (Acipenseridae) under conditions of normal and regulated flow. Journal of Ichthyology **12:** 608–616.

Lake Michigan Lake Sturgeon Task Group. 2005. Guidelines for genetic conservation, propagation and stocking of lake sturgeon in Lake Michigan. Draft document.

LaHaye, M., A. Branchaud, M. Gendron, R. Verdon, and R. Fortin. 1992. Reproduction, early life history, and characteristics of the spawning grounds of the lake sturgeon (*Acipenser fulvescens*) in Des Prairies and L'Assomption Rivers, near Montreal, Quebec. Canadian Journal of Zoology **70:**1681–1689.

Lavis, D. S., A. Hallett, E. M. Koon, and T. C. McAuley. 2003. History and advances in barriers as an alternative method to suppress sea lampreys in the Great Lakes. Journal of Great Lakes Research **29:** 362–372.

Li, H. W., C. B. Shreck, and K. J. Rodnick. 1984. Assessment of habitat quality models for cutthroat trout (*Salmo clarki clarki*) and coho salmon (*Oncorhynchus kitsutch*) for Oregon's coastal streams. Pages 57–111 in J. W. Terrell, editor. Proceedings of a workshop on fish habitat suitability index models. Biological report 85(6), U.S. Department of the Interior, U.S. Fish and Wildlife Service, Division of Biological Services, Washington, D.C.

Madison, G., and R. N. Lockwood. 2004. Manistique River assessment. Fisheries special report 31, Michigan Department of Natural Resources, Ann Arbor, Michigan.

McCabe, G. T., and C. A. Tracy. 1994. Spawning and early life history of white sturgeon, *Acipenser transmontanus*, in the lower Columbia River. Fishery Bulletin **92:**760–72.

McKeown, B. A. 1984. Fish migration. Timber Press, Portland, Oregon.

McKinley, S., G. Van Der Kraak, and G. Power. 1998. Seasonal migrations and reproductive patterns in the lake sturgeon, *Acipenser fulvescens*, in the vicinity of hydroelectric stations in northern Ontario. Environmental Biology of Fishes **51:**245–256.

Paragamian, V. L., G. Kruse, and V. Wakkinen. 2001. Spawning habitat of Kootenai River white sturgeon, post-Libby Dam. North American Journal of Fisheries Management **21:**22–33.

Parsley, M. J., P. J. Anders, A. I. Miller, L. G. Beckman, and G. T. McCabe Jr. 2002. Recovery of white sturgeon populations through natural production: understanding the influence of abiotic and biotic factors on spawning and subsequent recruitment. American Fisheries Society Symposium **28:**55–66.

Parsley, M. J., L. G. Beckman, and G. T. McCabe Jr. 1993. Spawning and rearing habitat use by white sturgeons in the Columbia River downstream from McNary Dam. Transactions of the American Fisheries Society **122:**217–227.

Pizzuto, J. 2002. Effects of dam removal on river form and process. Bioscience **52:**683–691.

Rochard, E., G. Castelnaud, and M. LePage. 1990. Sturgeons (Pisces: Acipenseridae): threats and prospects. Journal of Fish Biology **37:** 123–132.

Rubec, P. J., J. C. W. Bexley, H. Norris, M. S. Coyne, M. E. Monaco, S. G. Smith, and J. S Ault. 1999. Suitability modeling to delineate habitat essential to sustainable fisheries. American Fisheries Society Symposium **22:**108–133.

Ryan, P. A., R. Knight, R. MacGregor, G. Towns, R. Hoopes, and W. Culligan. 2003. Fish-community goals and objectives for Lake Erie.

Great Lakes Fishery Commission special publication 03-02, Ann Arbor, Michigan.

Santy, K. L. 2001. Lower Fox River integrated management plan. Wisconsin Department of Natural Resources Publication WT-666-2001, Green Bay.

Schneeberger, P. J., R. F. Elliott, J. L. Jonas, and S. Hunt. 2005. Benthivores. Pages 25–32 in M. E Holey and T. N. Trudeau, editors. The state of Lake Michigan in 2000. Great Lakes Fishery Commission Special Publication 05–01. Great Lakes Fishery Commission, Ann Arbor, Michigan.

Schneider, I. C., T. J. Lynchwick, E. J. Trimberger, J. H. Peterson, R. O'Neal, and P. T. Schneeberger. 1991. Walleye rehabilitation in Lake Michigan, 1969–1989. Pages 23–61 in P. J. Colby, C. A. Lewis, and R. L. Eschenroder, editors. Status of walleye in the Great Lakes: case studies prepared for the 1989 workshop. Great Lakes Fishery Commission special publication number 91-1, Ann Arbor, Michigan.

Scott, W. B., and E. J. Crossman. 1973. Freshwater fishes of Canada. Bulletin 184. Fisheries Research Board of Canada, Ottawa, Canada.

Threader, R. W., R. J. Pope, and P. R. H. Schaap. 1998. Development of a habitat suitability index model for lake sturgeon (*Acipenser fulvescens*). Ontario Hydro report number H-07015.01-0012, Toronto, Canada.

Thuemler, T. F. 1997. Lake sturgeon management in the Menominee River, a Wisconsin-Michigan boundary water. Environmental Biology of Fishes **48:**311–317.

Veshchev, P. V., and A. S. Novikova. 1988. Reproduction of sevryuga, *Acipenser stellatus*, in the lower Volga. Journal of Ichthyology **28:**3–47.

Williot, P., E. Rochard, G. Castlenaud, T. Rouault, R. Brun, M. Lepage, and P. Elie. 1997. Biological characteristics of European Atlantic sturgeon, *Acipenser sturio*, as the basis for a restoration program in France. Environmental Biology of Fishes **48:**359–370.

Wisconsin Department of Natural Resources. 2002. Wisconsin trout streams. Report number PUH-FH-806 2002, Madison, Wisconsin.

Wisconsin Department of Natural Resources. 2004. The Wisconsin Lake sturgeon management plan: objectives and recommendations. Draft document, Madison, Wisconsin.

Zollweg, E. C., R. F. Elliott, T. D. Hill, H. R. Quinlan, E. Trometer, and J. W. Weisser. 2003. Proceedings of the 2002 Great Lakes lake sturgeon coordination meeting. Great Lakes Fishery Trust Workshop, Lansing, Michigan.